

Spectral indices of radio loops

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Spectral indices of radio loops

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Abstract. Observations of the continuum radio emission at 1420, 820 and 408 MHz enabled estimations of the brightness of the radio loops. We calculated the mean brightness temperatures and surface brightnesses of the six main Galactic radio-continuum loops I-VI at the three frequencies. We have demonstrated the reality of Loops V and VI and presented diagrams of their spectra for the first time. We derived the radio spectral indices of Galactic radio loops from radio surveys at three frequencies. The method we have developed for large radio loops, was also used for smaller ones. In this paper we also estimated the temperatures and brightnesses of the Monoceros radio loop at 1420, 820 and 408 MHz and of Cygnus loop. The spectra (mean temperature versus frequency) between the three frequencies, as well as the $T - T$ graphs, are estimated and the spectral indices are also obtained. Using the supernova remnant (SNR) hypothesis for the origin of radio loops, distances are calculated from the surface brightnesses and the angular diameters. The obtained results confirm non-thermal origin of all radio loops and we show that our method is applicable to almost all SNRs.

1. Introduction

It is very well known that some radio spurs can be joined into small circles. The sets of spurs which form small circles are called loops. During the early seventies, four major loops were recognized. Their discoveries and studies took place in this order: Loop I [1, 2, 3, 4], Loop II [1, 5, 4], Loop III [5, 4] and Loop IV [3, 4, 6]. In 1970. Salter gave the most precise determination of these circles' parameters, which were later published in [7]. A detailed review of the subject was published in [8]. In Refs. [9] and [10] it was made an observation that some other spurs could be connected into loops V and VI. Later, we have demonstrated [11] the probable existence of Loops V and VI. In general, they display shell structure and have non-thermal spectra, similar to the main loops I-IV which are usually assumed to be SNRs.

A star in the constellation of Cygnus exploded and its remnant is Cygnus loop. It is classified as a middle-aged SNR located below (but near the plane of) the Galactic equator less than 1 kpc away from us. It is listed in Green's catalogue of SNRs as G74.0-8.5 [12, 13, 14]. The Monoceros loop was considered as an object similar to major loops [15]. Monoceros Nebula can be found in a catalog of Galactic SNRs listed as G205.5+0.5 [12, 13, 14].

Basic characteristics of Monoceros and Cygnus loop, as well as many other Galactic loops, can be found in a catalog of Galactic SNRs [12, 13, 14]. In Ref. [16], the SNRs that lie less than ~ 2 kpc away from the Earth are discussed and classified by distance to the Earth. The data on Galactic supernova remnants, in all the spectral bands, also may be found in [17, 18].

In order to study the structure of Galactic radio loop emission, it is necessary to determine their spectral indices. Here we present a short overview of our recent investigations in this field.

2. Analysis and method

The aim of our work was to investigate the spectral indices of radio loops. First we derive the average brightness temperatures and surface brightnesses at 1420, 820 and 408 MHz of the six main Galactic radio-continuum loops and of the Monoceros and Cygnus loop, as well as their radio spectral indices. The temperatures, surface brightnesses and the radio spectral indices of the radio loops are computed using data taken from radio-continuum surveys at 1420, 820 and 408 MHz. Diameters and distances of Loops I-VI were also calculated, as well as diameter and distance of Monoceros loop. We also demonstrate the reality of Galactic radio Loops V and VI. The spectral indices of Loops V and VI, Monoceros and Cygnus loop are also obtained from $T - T$ plots.

As it is said in Ref. [19] contour lines, which correspond to the minimum and maximum brightness temperatures for each spur, are taken to define their borders. The contour line T_{\min} is the the lower temperature limit between the background and the spur, and T_{\max} is the upper temperature limit between the spur and unrelated confusing sources (superposed on the spur and hence requiring elimination from the calculation). In this manner, background radiation was considered as radiation that would exist if there were no spurs. We used averages over the data within these two curves: the contour for T_{\min} and the contour for T_{\max} . The loop area was divided into different sections which correspond to spurs. The background radiation was subtracted in the following way: the temperature of the loop with the background added was determined at first. After that the temperature of the background near the loop was determined. Finally, the difference of these two values was calculated.

The method for determination of the brightness temperature given in article [19] was developed for large radio loops (I-VI), but later on we applied it to much smaller loops (Monoceros and Cygnus) and showed that it is rather efficient in the case of smaller radio loops.

3. Results and discussion

We used radio-continuum surveys at three frequencies: 1420 MHz [20], 820 MHz [21], 408 MHz [22] and calculated the corresponding mean temperatures and brightnesses [23, 24, 19, 11, 25, 26, 27]. Knowing three values of brightnesses, the spectral indices could be calculated as coefficients of the linear fits of logarithmic temperature versus frequency plots.

Figs. 1 - 4 show main Galactic radio Loops I-IV at 1420, 820 and 408 MHz, with two contours representing the temperatures T_{\min} and T_{\max} , e.g. the borders of the loops. These borders are determined using given method. The right panel of Fig. 4 shows temperature scales in K, for 1420, 820 and 408 MHz.

The initial assumption in our investigation was the supernova remnant (SNR) hypothesis for the origin of radio loops, we are supposing all radio loops to be SNRs [28, 29, 30, 8]. We also study how results for brightnesses and distances of radio loops agree with current theories of SNR evolution. For this purpose, the ambient density and initial explosion energy of the loops are discussed [11]. We also discuss applications of different $\Sigma - D$ relations [19, 11, 26].

After deriving the brightness temperature T_b , we have converted these values into surface brightness Σ_ν by:

$$\Sigma_\nu = (2k\nu^2/c^2)T_b, \quad (1)$$

where k is Boltzmann constant and c is the speed of light.

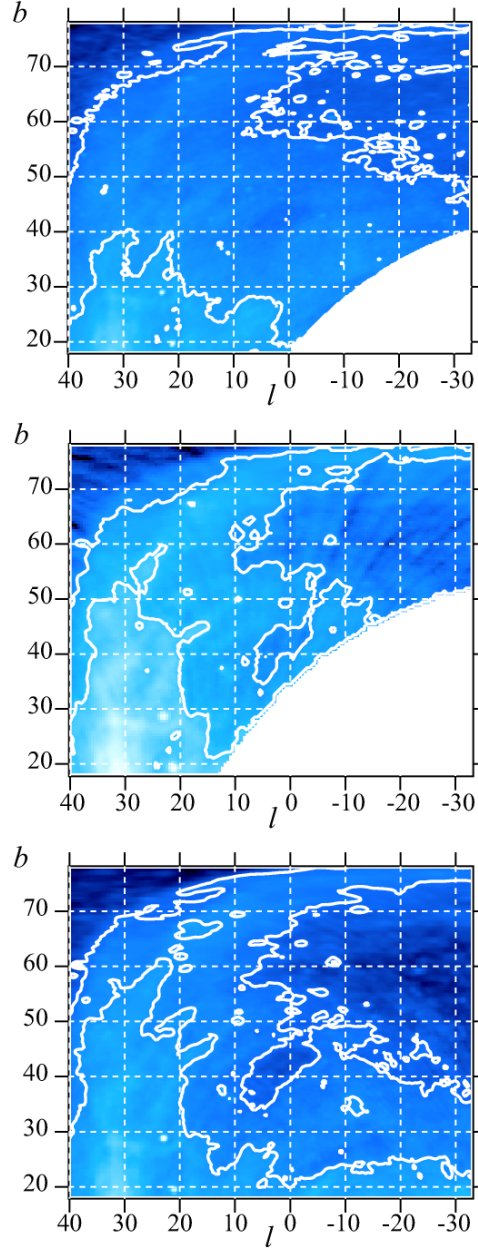


Figure 1. The area of Loop I at 1420 (top), 820 (middle) and 408 MHz (bottom), with contours of brightness temperature. Two contours are plotted, which represent the temperatures T_{\min} and T_{\max} , as given in Table 1 in Ref. [19]. White areas in the top and bottom pictures signify that no data exist there at 1420 and 820 MHz. This contains the part of the North Polar Spur normal to the Galactic plane: $l = [40^\circ, 0^\circ]$; $b = [18^\circ, 78^\circ]$ and its part parallel to the Galactic plane: $l = [360^\circ, 327^\circ]$; $b = [67^\circ, 78^\circ]$.

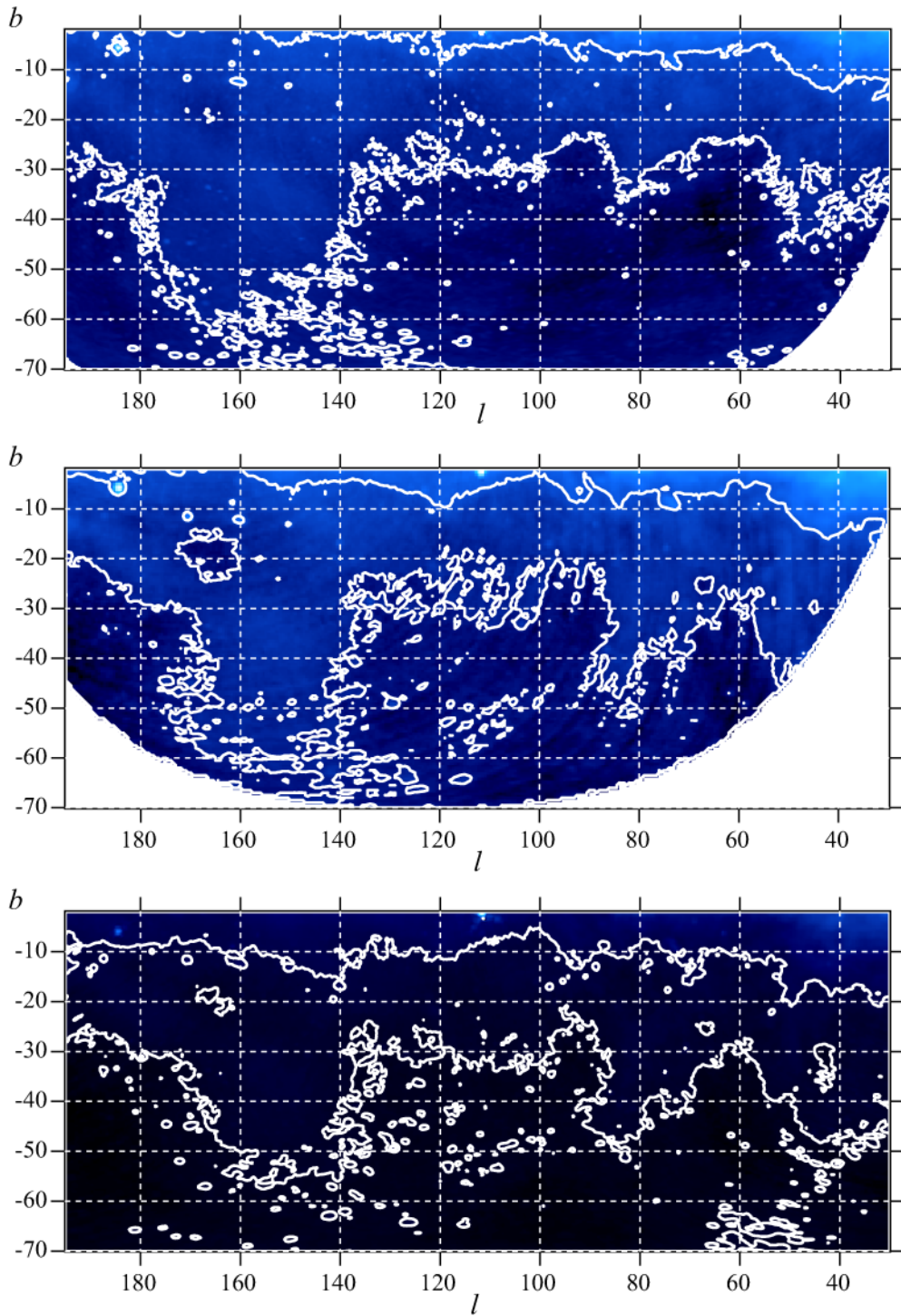


Figure 2. The same as Fig. 1, but for Loop II. White areas in the top and bottom pictures signify that no data exist there at 1420 and 820 MHz. Spurs belonging to this radio loop have positions: $l = [57^\circ, 30^\circ]$; $b = [-50^\circ, -10^\circ]$ for spur in Aquarius and $l = [195^\circ, 130^\circ]$; $b = [-70^\circ, -2^\circ]$ for spur in Aries.

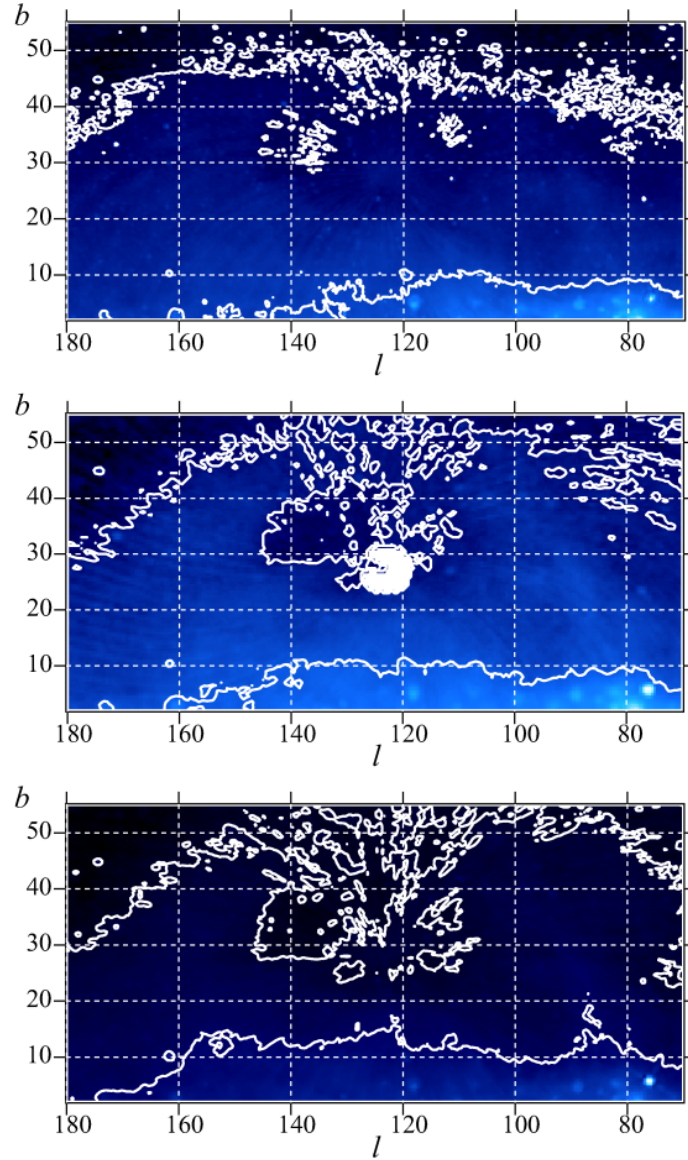


Figure 3. The same as Fig. 1, but for Loop III. The white area in the center of the picture for 820 MHz signifies that no data exist there at that frequency. Spurs belonging to this radio loop have positions: $l = [180^\circ, 135^\circ]$; $b = [2^\circ, 50^\circ]$ and $l = [135^\circ, 110^\circ]$; $b = [40^\circ, 55^\circ]$ for first spur and $l = [110^\circ, 70^\circ]$; $b = [6^\circ, 50^\circ]$ for second one.

Assuming the spectra to have a power-law form:

$$T_b = K\nu^{-\beta}, \quad (2)$$

we get:

$$\log T_b = \log K - \beta \log \nu, \quad (3)$$

where β is the spectral index and K is a constant.

Knowing the values of brightnesses (at 1420, 820 and 408 MHz) we were able to derive spectral indices from fitting equation (3) to the data. The spectra were generated using mean temperatures at three different frequencies. This best-fit straight line spectrum enables

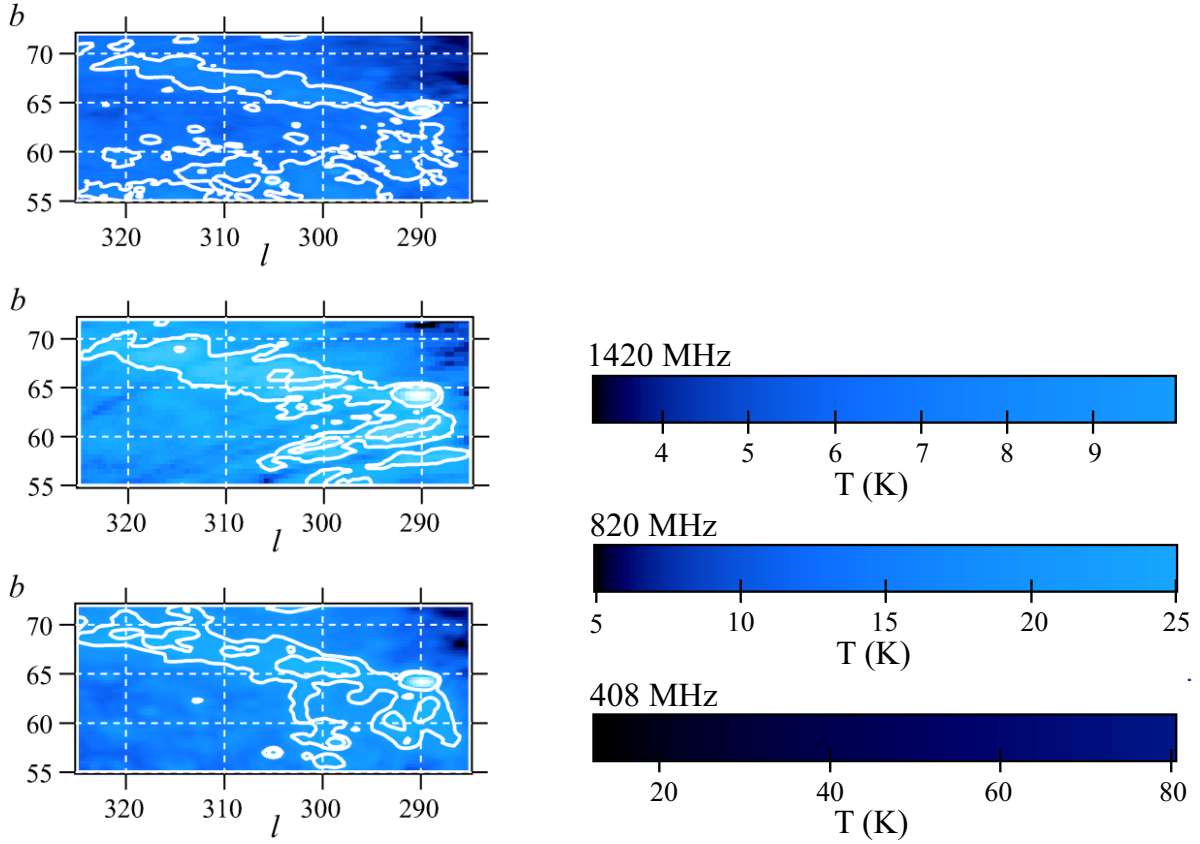


Figure 4. *Left panel:* The same as Fig. 1, but for Loop IV. This radio loop has position: $l = [330^\circ, 290^\circ]$; $b = [48^\circ, 70^\circ]$. *Right panel:* Temperature scales for 1420, 820 and 408 MHz. All are given in K and they are used for all previous pictures of the radio loops.

calculation of spectral index as negative value of the line's direction coefficient. The obtained values of radio spectral indices for large Galactic Loops I-VI are 2.74 ± 0.08 , 2.88 ± 0.03 , 2.68 ± 0.06 , 2.90 ± 0.28 , 3.03 ± 0.15 and 2.90 ± 0.09 , respectively [19]. For smaller SNRs Monoceros and Cygnus, the values are: 2.70 ± 0.14 [26] and 2.76 ± 0.03 [31], respectively. The values obtained (all greater than 2.2) confirm a non-thermal origin for the emission from the radio loops.

The radio spectral index β can be also determined from $T - T$ plot, between the pair of frequencies ν_1 and ν_2 , by the relation:

$$T_{\nu_1}/T_{\nu_2} = (\nu_1/\nu_2)^{-\beta}, \quad (4)$$

from which we have

$$\beta = \log(a_{12})/\log(\nu_1/\nu_2), \quad (5)$$

where a_{12} is direction coefficient of line $T_{\nu_2}(T_{\nu_1})$. In that way, for Loops V and VI obtained spectral indices from $T - T$ plots are 2.90 ± 0.11 and 2.77 ± 0.13 , respectively [11]. For Monoceros loop we obtained 2.63 ± 0.30 [26] and for Cygnus 2.78 ± 0.41 [31].

By use of the spectral indices, the brightnesses have been extrapolated to 1 GHz according to relation:

$$\Sigma_{1\text{GHz}}/\Sigma_{\nu\text{GHz}} = (\nu/1)^{(\beta-2)}. \quad (6)$$

Applying relation (6), the brightness at any frequency become reduced to brightness at 1 GHz, so the results become comparable.

The obtained results confirm a non-thermal origin and nearby locations for the Galactic radio loops. Therefore, we have indications that they are very old SNRs that evolve in low ambient densities, with high initial explosion energies [11].

4. Conclusions

The main results of our investigation may be summarized as follows:

- Our results are consistent with the SNR hypothesis and suggest that the main Galactic radio loops may have a SNR origin [23, 24, 19].
- We note that our values for spectral indices are in between the corresponding values for Loops I and III given in [32] and [33] ([19]). In case of the main Galactic radio loops we used $\Sigma - D$ relations for supernova remnants by [34]. The estimated distances of the main radio loops derived using the 1420 MHz data are in good agreement with the earlier results (e.g. [35]).
- In our papers, we present the first radio-continuum spectra for the main radio loops, plus Loops V and VI, made by using average brightness temperatures at three different frequencies. We find that good linear fits can be made to each of these, supplying accurate spectral indices. The radio spectra of the loops are fitted rather well by power-law spectra which is consistent with a SNR origin for these features [19].
- We have estimated the distances of the main Galactic radio loops and Loops V and VI from the northern-sky radio continuum survey at 1420 MHz [20] using two different $\Sigma - D$ relations. The estimated distances of the main radio loops derived using the 1420 MHz data are in good agreement with the earlier results (e.g. [35]) [19, 11]. From the $\Sigma - D$ diagram at 1 GHz taken from [36] with the derived values for the six loops superposed, it can be concluded that the surrounding density of the main radio loops, plus Loops V and VI, is low and that the explosion energy is high. Further, the locations of the Loops on this $\Sigma - D$ diagram agree with the general distribution and this strengthens the idea that they are old SNRs [11].
- From the spectral index analysis we can confirm that the emission from the radio loops is non-thermal in origin. We have demonstrated the probable existence of Loops V and VI. The distances and spectral indices of Loop V and Loop VI are estimated. In general, they display shell structure and have non-thermal spectra, similar to the main loops I-IV which are usually assumed to be SNRs.
- We calculated the brightness temperatures and surface brightnesses of the Monoceros radio loop at 1420, 820, and 408 MHz. The linear spectrum is estimated for mean temperatures versus frequency between 1420, 820, and 408 MHz. It is the first time that the brightness temperatures of the Monoceros loop are calculated at 820 and 408 MHz frequencies from the observational data. We sampled much more points (more than 1000) at 1420 MHz than in previous papers (95 points) [37, 38]. Also, the brightness temperature is now derived using a different method. The temperature of this radio loop at 1420 MHz is in good agreement with the result obtained in [37] ([25, 26]).
- In case of the Monoceros radio loop we used empirical $\Sigma - D$ relations for supernova remnants by Urošević [39] and Arbutina et al. [40]. The estimated distance of the Monoceros radio loop is in good agreement with the earlier results [13]. The spectral index analysis confirms the non-thermal origin of the Monoceros radio loop [26].
- We present the radio continuum spectrum of the Cygnus loop using average brightness temperatures at three different frequencies. Linear fit provides reliable spectral index.

Obtained results are consistent with the SNR hypothesis and suggest that the Cygnus radio loop may have a SNR origin. Also, we derived the $T - T$ plots which enables also calculation of spectral index. [27].

According to the results summarized in this paper, one can conclude that radio loop emission of the six main Galactic radio-continuum loops, Monoceros and Cygnus loop is in good agreement with current theories of SNR evolution.

We showed that method for defining a loop border and for determining the values of temperature and brightness, which we developed for main Galactic loops I-VI, could be applicable to all SNRs.

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